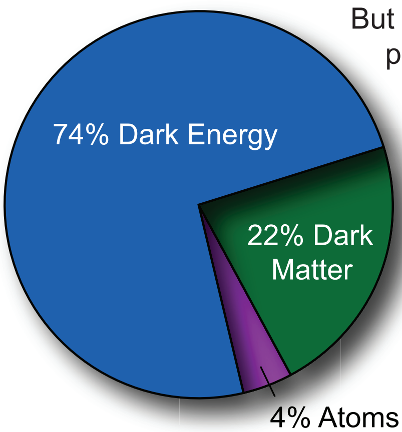
the quest for dark energy

NASA's Quest for Dark Energy

In 1998, astronomers made an astounding discovery that shook the foundations of modern physics: contrary to expectations, the expansion of our Universe is revving up. We live in a runaway Universe, where the most distant observable galaxies are racing away from us at breakneck speeds.

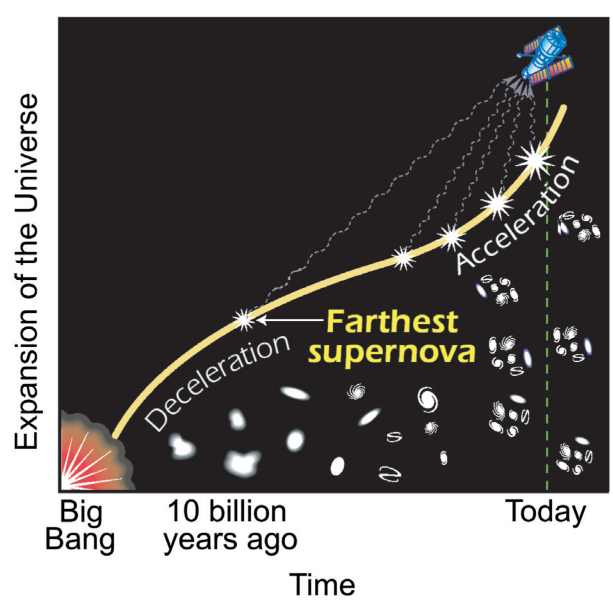


But what is causing this cosmic acceleration? No one knows for certain—perhaps it is a manifestation of the cosmological constant that Albert Einstein had postulated in his general theory of relativity. Physicist Michael Turner coined the generic term "dark energy" to describe the mysterious force at play. Whatever dark energy actually is, detailed measurements reveal that it comprises a whopping 74% of our Universe's total mass-energy budget!

Besides being the Universe's dominant form of energy, dark energy must be playing a crucial role in determining how the cosmos evolves, and it will determine whether our Universe expands forever or collapses upon itself. Many scientists think that understanding dark energy will revolutionize physics just as the theory of relativity and quantum mechanics did nearly a century ago. Explaining dark energy's nature is thus one of the great mysteries in modern physics, and NASA is at the forefront of the endeavor to solve it.

The First Evidence for Dark Energy

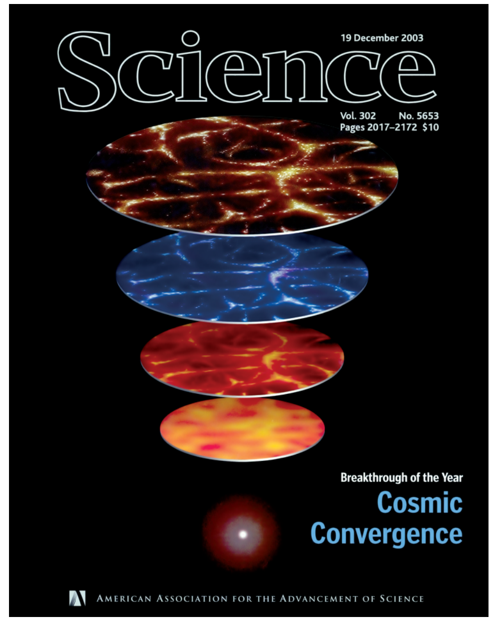
Astronomers have known since the late 1920s that the Universe is expanding, because they see distant galaxies rushing away from Earth faster than nearby galaxies. Physicists long assumed that the combined gravitational attraction of all the hundreds of billions of galaxies in the Universe would gradually slow down cosmic expansion. During the 1990s two competing groups set out to measure the geometry of the Universe and its rate of deceleration.



But their studies turned conventional wisdom on its head. Both teams reported in 1998 that they had found the opposite effect of what they had expected to measure. The Universe's expansion is actually speeding up!

The two groups reached this conclusion by monitoring cosmic explosions called Type Ia supernovae. These occur when a white dwarf, the dead core of a star, "feeds" on or merges with a nearby orbiting star. When its mass exceeds 1.4 times the Sun's mass, it blows itself to smithereens in a supernova explosion. Since the explosion always occurs at about the same mass, Type Ia supernovae are all similar in intrinsic brightness and they serve as excellent "standard candles."

Just as a light bulb appears brighter when it's closer than when it's farther, astronomers can compare a standard candle's observed brightness to its intrinsic brightness to measure its distance. By observing many Type Ia supernovae in receding galaxies across our Universe, astronomers can determine the distance to the host galaxies. When combined with spectral data that gives their recession speeds, this yields information about how fast our Universe was expanding at different epochs. Both teams found that the Universe was expanding more slowly in the past than it is now.



The WMAP result on dark energy and cosmology was hailed as the top scientific breakthrough of 2003 by Science magazine. (Cover image reprinted with permission from AAAS.)

Theorists have proposed numerous ideas to explain dark energy, but the most popular idea is that the presence of dark energy is a property of "empty" space. This idea was originally proposed by Einstein in 1917, shortly after he formulated his general theory of relativity. Einstein postulated that empty space contains an outward pressure—a cosmological constant—that perfectly counters gravity to maintain a static Universe as was then assumed to be the case. But when Edwin Hubble discovered cosmic expansion in 1929, Einstein rejected his fudge factor and called it his greatest scientific blunder.

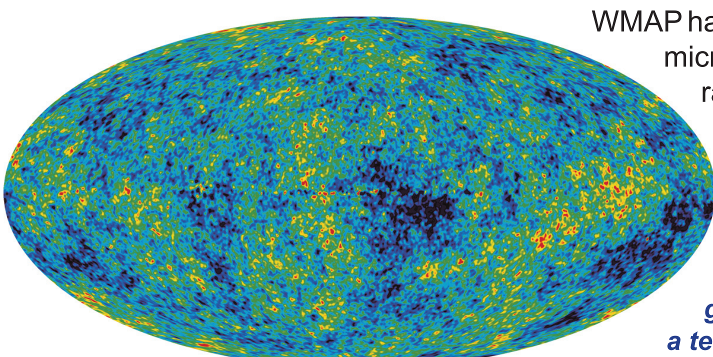
If dark energy is Einstein's cosmological constant, its strength in any given small volume of space is negligible, so we don't perceive its effects in everyday life or even in laboratory experiments. The phenomenon only truly manifests itself across billions of light-years of space—where astronomers can see the effects of galaxies rushing apart from one another. Since different theories make different predictions about dark energy's influence on cosmic expansion, the key to unlocking dark energy's secrets is to measure how fast our Universe was expanding at various epochs in its 13.7-billion-year history. This is where NASA comes in.

NASA Takes the Lead

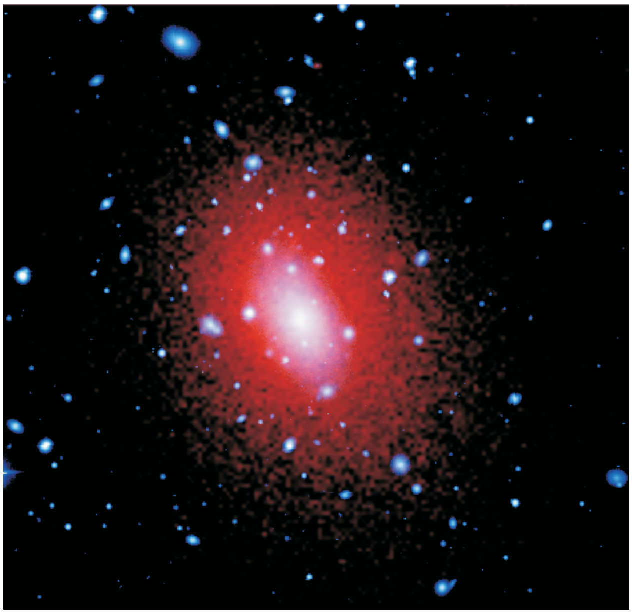
The two teams who co-discovered cosmic acceleration in 1998 primarily used ground-based optical telescopes to study Type Ia supernovae. But since then, NASA spacecraft such as the Hubble Space Telescope, the Wilkinson Microwave Anisotropy Probe (WMAP), and the Chandra X-ray Observatory have played leading roles in probing the history of cosmic expansion, giving the scientific community the independent confirmation that it needed to fully embrace the startling conclusion that cosmic acceleration is for real.

Hubble has extended ground-based studies by observing supernovae at much greater distances. The Hubble observations indicate that the Universe's expansion was actually decelerating for most of its history, as theory predicted. But about 5 to 6 billion years ago, it began to accelerate, and the rate of acceleration has continued to increase.

WMAP has provided independent confirmation by studying the cosmic microwave background (CMB), a radio hiss that is leftover radiation from the Big Bang. The CMB is nearly perfectly



WMAP provided a "baby picture" of our Universe. The detailed, all-sky picture of the infant universe from three years of WMAP data reveals 13.7 billion year old temperature fluctuations (shown as color differences). These correspond to the seeds that grew to become the galaxies and the voids between them. This image shows a temperature range of ± 200 microKelvin. (Image credit: NASA/WMAP Science Team.).



Galaxy Cluster Abell 2029
The red diffuse emission shows hot intergalactic gas, heated to about 100 million degrees by the enormous gravity in the cluster, and visible only in X-rays. Astronomers used the Chandra X-ray satellite to study clusters of galaxies such as this to make measurements of the effects of dark energy on the expansion of the Universe. (Image Credit: NASA/CXC/IoA/S.Allen et al.)

uniform in all directions, but some areas are slightly warmer or cooler than neighboring regions. These warm and cool spots correspond to regions in the early Universe that were slightly denser or less dense than average. These regions later influenced how gravity clumped matter together to form clusters of galaxies. By comparing how matter was clumped in the early Universe to how it has clumped in more recent times, along with measuring the angular size of the biggest clumps, cosmologists have determined that dark energy makes up 74% of the Universe's overall energy density. This result is consistent with the amount needed to explain the cosmic acceleration measured in the supernova studies.

Using Chandra, astronomers have measured the temperature and X-ray luminosity of the hot gas that permeates the space between galaxies in giant clusters. By comparing the X-ray emission of 26 different clusters ranging in distance from 1 billion to 8 billion light-years, the team found that the Universe began accelerating about 6 billion years ago, in good agreement with the Hubble and WMAP results.

Thanks to a powerful combination of ground-based programs and NASA missions, astronomers have made considerable strides in charting the Universe's expansion history. But it will require next-generation NASA missions to reveal the details of this evolution. And it's the details that will enable physicists to concentrate on the theories that best match the data.

The Beyond Einstein Program

Earlier this decade NASA developed the Beyond Einstein Program, which consists of a series of missions to probe fundamental questions about dark energy, black holes, and the very early Universe.

One of the missions is the Joint Dark Energy Mission (JDEM), which will focus on studying dark energy. JDEM is a partnership between NASA and the U.S. Department of Energy. In August 2006 NASA initiated the study of three mission concepts for JDEM: the Advanced Dark Energy Physics Telescope (ADEPT), the SuperNova/Acceleration Probe-Lensing (SNAP-L), and the Dark Energy Space Telescope (Destiny). The JDEM mission that actually flies will be determined by a future, open competition.

NASA Dark Energy Milestones

- **2001: Hubble finds evidence that the early Universe was decelerating as predicted.**
- **2003: WMAP confirms existence of dark energy.**
- **2004: Hubble finds new clues about the nature of dark energy.**
- **2004: Chandra uses new independent technique to measure dark energy.**
- **2006: Hubble confirms influence of dark energy in the young Universe.**

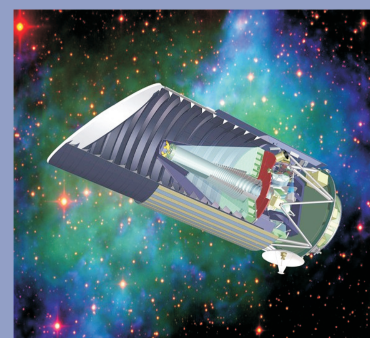
Two other Beyond Einstein missions, Constellation-X (Con-X) and the Laser Interferometer Space Antenna (LISA), will provide crucial independent measurements of dark energy. Con-X will consist of four X-ray telescopes inside one spacecraft, with mirrors providing 25 to 100 times more sensitivity than Chandra's mirrors. Con-X will address a variety of questions, but it will also contribute

The JDEM Mission Concepts Funded by NASA

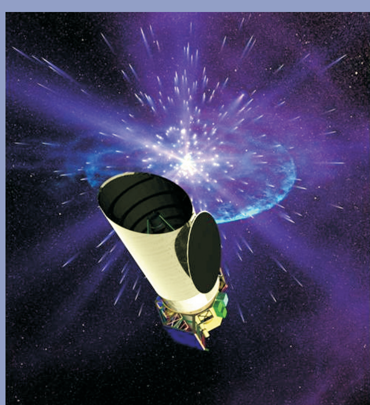
Artist's concept of the ADEPT spacecraft.

ADEPT, the Advanced Dark Energy Physics Telescope, is led by Charles Bennett of Johns Hopkins University in Baltimore, Maryland. ADEPT will use a 1.3-meter near-infrared telescope to locate 1,000 Type Ia supernovae and 100 million galaxies. The galaxy survey will be the most comprehensive ever of how galaxies are distributed over very large volumes of space. Scientists can then compare the distribution pattern to the CMB's tiny temperature fluctuations to determine how dark energy has influenced cosmic evolution.

SNAP-L, the SuperNova/Acceleration Probe-Lensing, is led by Saul Perlmutter at the Lawrence Berkeley Laboratory at the University of California, Berkeley. SNAP-L's powerful camera could pick up about 2,000 Type Ia supernovae each year over a wide range of distances. But SNAP-L will also conduct studies that take advantage of gravitational lensing, a phenomenon where the mass of a foreground object bends the light of distant galaxies like a lens. SNAP-L will measure the distortion in the galaxy shapes and this will enable a measurement of dark energy's influence on the distribution of matter in our Universe.



Artist's concept of the SNAP spacecraft.



Artist's concept of the Destiny spacecraft.

Destiny, the Dark Energy Space Telescope, is led by Tod Lauer of the National Optical Astronomy Observatory, based in Tucson, Arizona. Destiny's 1.65-meter near-infrared telescope could detect more than 3,000 Type Ia supernovae over the first two years of the mission. In its third year, Destiny would measure the positions and shapes of more than 200 million galaxies in a survey covering 1,000 square-degrees of sky. The measurements of galaxy shapes will reveal the influence of gravitational lensing. The positions, combined with CMB data, will help cosmologists measure how the large-scale distribution of matter in the Universe has evolved since the Big Bang.

greatly to dark energy studies. It will extend the Chandra studies of galaxy clusters to much greater distances, enabling astronomers to map the Universe's expansion history and study the growth of cosmic structure in much greater detail.

LISA will study gravitational waves, which are subtle ripples in the fabric of space-time predicted by Einstein's general theory of relativity. If LISA catches gravitational waves from a merging pair of black holes in a distant galaxy, and if astronomers can measure the distance to that galaxy, the combined information would provide a new way to measure the properties of dark energy.

Thanks to the key roles played by NASA spacecraft such as Hubble, WMAP, and Chandra, the scientific community was forced to accept the reality of dark energy. Cracking the mystery of dark energy will undoubtedly revolutionize many areas of science, and learning the Universe's dominant form of energy will stir the public's imagination as well. NASA spacecraft are continuing to explore the Universe in many different ways, and future NASA missions such as JDEM, Con-X, and LISA are poised to take the next giant leap in this quest for dark energy.

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